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Ignition on the National Ignition Facility: a path towards inertial fusion energy

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Abstract

The National Ignition Facility (NIF), the world's largest and most powerful laser system for inertial confinement fusion (ICF) and experiments studying high-energy-density (HED) science, is nearing completion at Lawrence Livermore National Laboratory (LLNL). NIF, a 192-beam Nd-glass laser facility, will produce 1.8 MJ, 500 TW of light at the third-harmonic, ultraviolet light of 351 nm. The NIF project is scheduled for completion in March 2009. Currently, all 192 beams have been operationally qualified and have produced over 4.0 MJ of light at the fundamental wavelength of 1053 nm, making NIF the world's first megajoule laser. The principal goal of NIF is to achieve ignition of a deuterium–tritium (DT) fuel capsule and provide access to HED physics regimes needed for experiments related to national security, fusion energy and for broader scientific applications.

The plan is to begin 96-beam symmetric indirect-drive ICF experiments early in FY2009. These first experiments represent the next phase of the National Ignition Campaign (NIC). This national effort to achieve fusion ignition is coordinated through a detailed plan that includes the science, technology and equipment such as diagnostics, cryogenic target manipulator and user optics required for ignition experiments. Participants in this effort include LLNL, General Atomics, Los Alamos National Laboratory, Sandia National Laboratory and the University of Rochester Laboratory for Energetics (LLE). The primary goal for NIC is to have all of the equipment operational and integrated into the facility soon after project completion and to conduct a credible ignition campaign in 2010. When the NIF is complete, the long-sought goal of achieving self-sustaining nuclear fusion and energy gain in the laboratory will be much closer to realization.

Successful demonstration of ignition and net energy gain on NIF will be a major step towards demonstrating the feasibility of inertial fusion energy (IFE) and will likely focus the world's attention on the possibility of an ICF energy option. NIF experiments to demonstrate ignition and gain will use central-hot-spot (CHS) ignition, where a spherical fuel capsule is simultaneously compressed and ignited. The scientific basis for CHS has been intensively developed (Lindl 1998 *Inertial Confinement Fusion: the Quest for Ignition and Energy Gain Using Indirect Drive* (New York: American Institute of Physics)) and has a high probability of success. Achieving ignition with CHS will open the door for other advanced concepts, such as the use of high-yield pulses of visible wavelength rather than ultraviolet and fast ignition concepts (Tabak *et al* 1994 *Phys. Plasmas* **1** 1626–34, Tabak *et al* 2005 *Phys. Plasmas* **12** 057305). Moreover, NIF will have important scientific applications in such diverse fields as astrophysics, nuclear physics and materials science.

This paper summarizes the design, performance and status of NIF, experimental plans for NIC, and will present laser inertial confinement fusion–fission energy (LIFE) as a path to achieve carbon-free sustainable energy.

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1. Introduction

The National Ignition Facility (NIF) is the US Department of Energy (DOE) and National Nuclear Security Administration (NNSA) national centre to study inertial confinement fusion (ICF) and the physics of extreme energy densities and pressures[1] [1]. NIF concentrates all the energy of its 192 extremely powerful laser beams onto a centimetre-scale fusion target, driving it to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF is designed to achieve target

[1] NIF web site, http://www.llnl.gov/nif/.

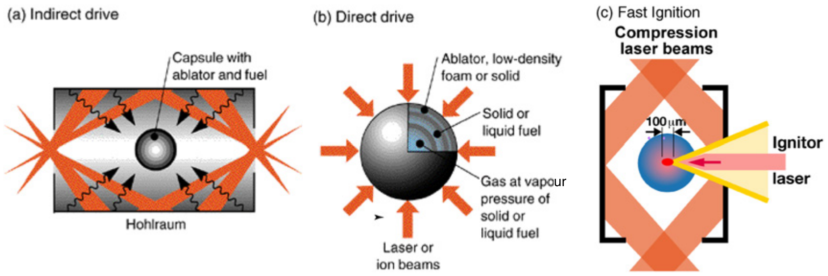

Figure 1. Illustration of ICF target concepts (*a*) indirect drive, (*b*) direct drive and (*c*) fast ignition.

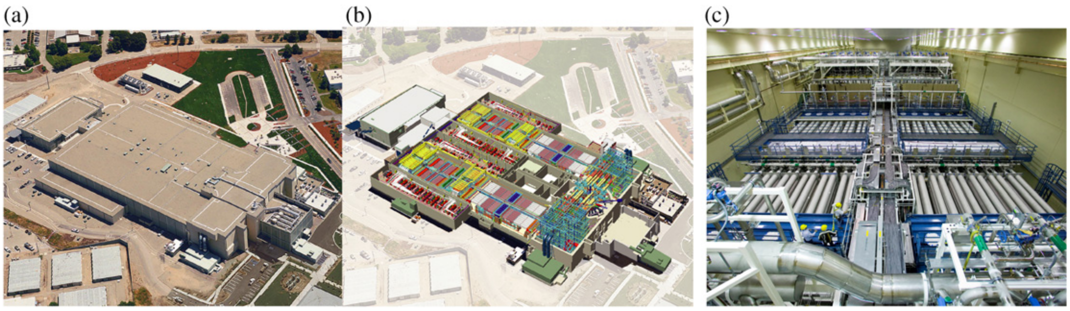

Figure 2. (*a*) NIF facility aerial photograph, (*b*) cut-away drawing and (*c*) Laser Bay 2.

temperatures of 100 million K, radiation temperatures over 3.5 million K, density of 1000 g cm^{-3} and 100 billion times atmospheric pressure. These conditions have never been created in a laboratory and exist naturally only in the interiors of the stars and during thermonuclear burn.

NIF will operate in the 'indirect-drive' configuration (figure 1(*a*)) where the fusion capsule [2], filled with a deuterium–tritium (DT) mixture, is mounted inside a cylindrical hohlraum. Laser beams enter the hohlraum through a hole in each end of the cylinder, are absorbed by the interior wall and converted to x-ray energy. These x-rays bathe the capsule and ablate its outer layer. Conservation of momentum requires that the remaining material implode or compress. Compression of the DT fuel to extraordinarily high temperature, pressure and density causes the central hot spot (CHS) to ignite, and a burn wave propagates through the remaining fuel [3]. NIF can also be configured in a 'direct-drive' arrangement (figure 1(*b*)) wherein the laser beams are directed onto the surface of the DT fuel capsule. Figure 1(*c*) illustrates the fast ignition concept [4, 5].

The mission to achieve thermonuclear ignition in the laboratory was identified in the early 1990s by DOE's Fusion Policy Advisory Committee and the National Academy of Sciences Inertial Fusion Review Group as the next important step in inertial fusion research. The experimental program to accomplish ignition [6] is detailed in the NIC plan [7], including all required science, technology and experimental equipment. The central goal of the NIC program is to perform credible ignition experimental campaigns on the NIF beginning in FY2010 and to transition NIF from project completion to routine facility operations in FY2012.

To prepare for the FY2010 ignition campaign, many activities are under way at NIF and other medium-scale facilities including OMEGA at LLE, Z at Sandia National Laboratory (SNL), Trident at Los Alamos National Laboratory (LANL) and Jupiter at Lawrence Livermore National Laboratory (LLNL). Experiments at these facilities are being used to develop and demonstrate shock timing, laser ablation and the diagnostics techniques needed to achieve ignition. In addition, the NIC team is conducting a simulated campaign that is stepping through the processes of preparing and executing the NIC to refine requirements on targets, diagnostics, lasers, optics, data collection and analysis, and to optimize the NIC strategy and shot plans to balance risk and resources.

2. The NIF

The NIF is designed to achieve ignition of a DT nuclear fusion target. As of September 2008, the facility is 98.5% complete, with the project on schedule for completion in March 2009. NIF's 192 laser beam lines are housed in a building with a volume of about 350 000 m^3 (figure 2). Each laser beam line contains 36 to 38 large-scale precision optical elements, depending on beam line configuration (figure 3), and hundreds of smaller optical components. The combined total area of precision optical surfaces is 3600 m^2, and the total radiating aperture is 22 m^2. For the purpose of comparison, the combined optical surface area of the two Keck telescopes, the world's largest, is 152 m^2, approximately 4% of NIF's. The NIF's 10 m diameter high-vacuum target chamber (figure 4) contains entry ports for all the laser beams and over 100 ports for diagnostic instrumentation and target insertion. Sophisticated diagnostic instruments such as x-ray and neutron spectrometers, microscopes and streak cameras, can be mounted around the equator and at the poles of the target chamber. About 35 different types of diagnostics are planned for NIC. For indirect-drive fusion studies, all 192 beams will be focused into a cylindrical hohlraum through two round entrance holes 2.5 mm in diameter. The conditions created in the hohlraum will

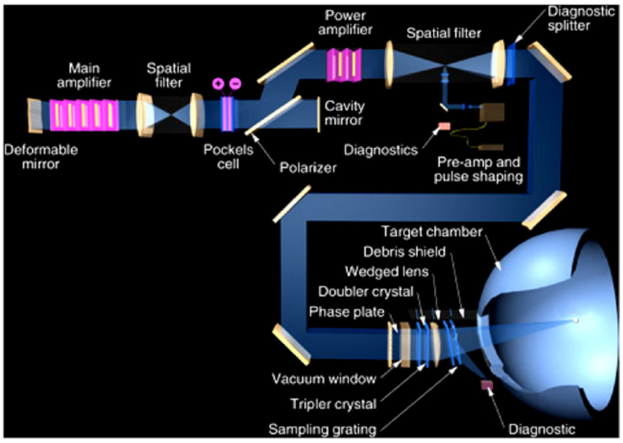

Figure 3. Schematic of one of NIF's 192 beamlines.

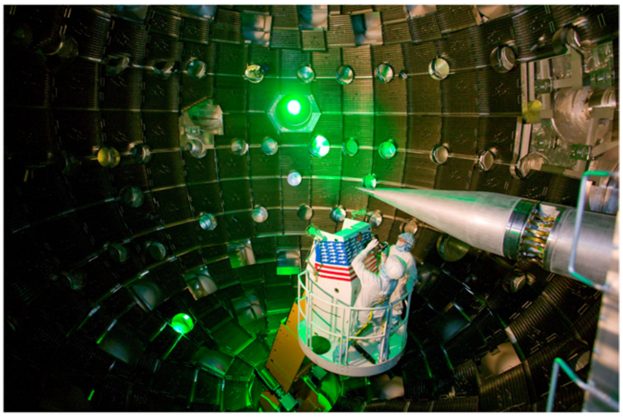

Figure 4. Inside the NIF target chamber, a 10 m diameter sphere of 10 cm thick aluminium coated with a 40 cm thick neutron shielding concrete shell. The entire assembly weighs about one-half million kilograms. The target positioner is on the right.

provide the necessary environment to explore a wide range of high-energy-density (HED) physics experiments, including laboratory-scale thermonuclear ignition and burn. All of the 192 beam lines have been operated at the fundamental 1053 nm wavelength (1ω), delivering greater than 19 kJ per beam line. At this time, 56 beam lines have been delivered to the NIF target chamber and frequency converted to the third-harmonic wavelength (3ω) of 351 nm.

The initial laser pulse is produced by a cw Yb-fibre master oscillator. The initial pulse passes through an array of fibre-optical components used to provide the required precise temporal shape and bandwidth, then is split 48 ways, sending pulses into the preamplifier modules. Pulses from each of the 48 preamplifier modules are further split and delivered into the 192 beam lines. Each beam line, illustrated in figure 2, operates as a four-pass amplifier, enabled by the LLNL invention of the large aperture plasma-electrode Pockels cell (PEPC) [8]. The PEPC functions as follows: a pulse is injected into each beam line near the focal plane of the transport spatial filter (TSF), from where it expands to the full square-aperture beam size of $37.2 \times 37.2\,\mathrm{cm}^2$, then passes through the spatial filter lens, which collimates the beam. The pulse passes through the power amplifier (PA), reflects from a mirror and a polarizer, then passes through the cavity spatial filter (CSF) and main amplifier (MA). It reflects from a deformable mirror used to correct wavefront distortions and then makes a second pass through the MA and CSF. During the time required for the pulse to make this double pass, voltage is applied to the PEPC that rotates the polarization of the pulse by 90°. It then passes through the polarizer, reflects from a second mirror and makes another double pass through the PEPC, CSF and MA. Before the pulse returns to the PEPC, its voltage is switched off, so the pulse reflects from the polarizer and mirror and makes a final pass through the PA and TSF and propagates on to the switchyard. There, beam transport mirrors direct the pulse through a final optics assembly (FOA), shown in figure 5, consisting of a 1ω vacuum window, focal-spot beam-conditioning optics, two frequency conversions that change the wavelength to 351 nm, a focal lens, main debris shield that also serves as a diagnostic beam splitter and a thin, disposable debris shield used to protect the optics from debris produced by irradiation of the target.

Also new for NIF is the introduction of the line-replaceable unit (LRU) design concept [9]. In this concept, developed at LLNL by the Atomic Vapour Laser Isotope Separation Program, the laser is assembled using modular components that are easily removed for maintenance, thus allowing the laser to maintain nearly continuous operation. Other key developments essential to the success of NIF are a continuous pour method for producing extremely low-defect laser glass [10], rapid growth of large, frequency-conversion crystals of potassium dihydrogen phosphate (KDP) and deuterated KDP [11] and the LLNL-developed strategy for increasing damage resistance and economically managing optical damage. Complete description of these key developments is beyond the scope of this paper; details can be found in the cited references.

3. The NIC

The NIC is a collaborative effort by LLNL, General Atomics (GA), LLE, LANL and SNL to perform a credible ignition experimental campaign on the NIF in FY2010 and continued campaigns past FY2010. NIC is separate from the NIF project, but planning and schedules are highly integrated, and both must be completed on schedule to support the NIC. The high-level NIC timeline is summarized in figure 6.

Components of the NIC plan include target physics, systems engineering and operations as well as targets and equipment such as target diagnostics, the cryogenic target positioner and user optics required for the ignition experiment. The first effort to achieve ignition will be by indirect-drive ICF using target designs that have been calculated to ignite at an energy of approximately 1 MJ for 3ω pulses. Key elements of the NIC plan are

- design, fabrication and execution of ignition experiments.
- Experiments on NIF and supporting NNSA experimental facilities prior to the FY2010 ignition experimental campaign that are needed to verify and validate the ignition design and mitigate risks.
- Diagnostics, user optics, cryogenic target system, targets, personnel and environmental protection systems, NIF operations personnel and operating inventory.

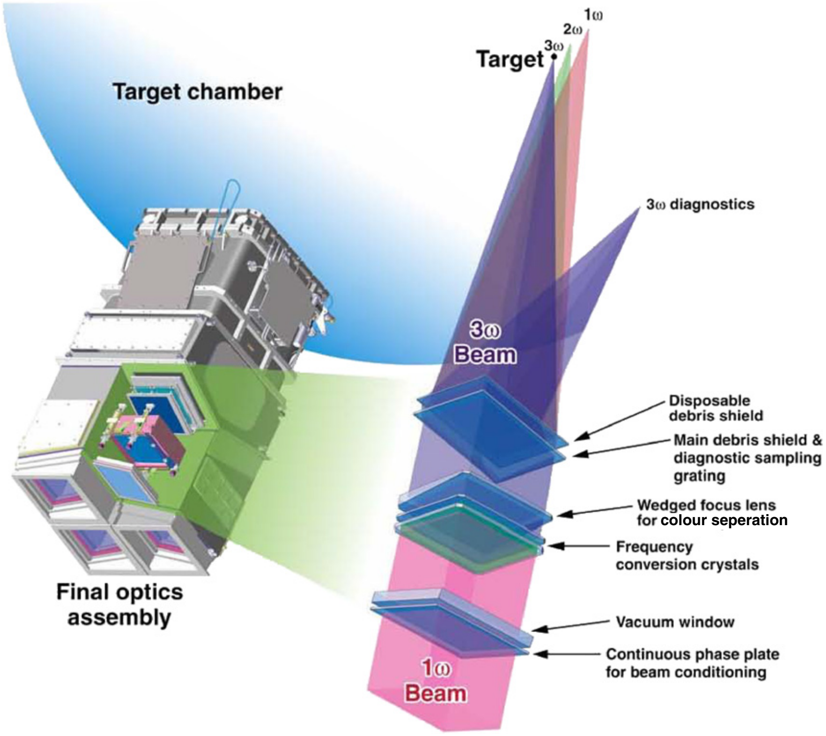

Figure 5. NIF FOA containing a beam-conditioning phase plate, KDP frequency-conversion crystals, fused-silica focus lens and two fused-silica debris shields.

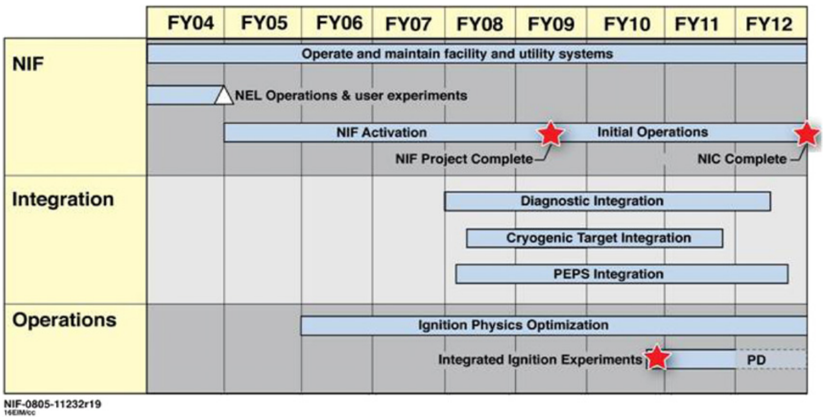

Figure 6. Timeline for integrating the NIF Project and NIC.

- Equipment and technology needed to maintain a sustained effort on ignition beyond the initial experimental campaigns.

Creating a NIF target requires the joint efforts of target designers, materials scientists and engineers. Targets for the NIC experiments are being developed by scientists and engineers from LLNL, GA, LLE and LANL working in collaboration. Designers establish specifications for the target, which typically are only a few millimetres in size. Their complicated shapes must be machined to meet precise requirements, including specifications for density, concentricity and surface smoothness. Nanoscale materials developed for NIF experiments include high-density carbon, very low-density copper and gold foams and graded-density foams.

The conditions that targets will encounter during the experiments make their performance highly sensitive to imperfections in fabrication. Manufacturing requirements for all the NIF targets, thus, are extremely rigid. Components must be machined to within an accuracy of 1 μm, with joints as small as 100 nm. In addition, the margin of error for target assembly is less than 8 μm. The current design for the ignition target is a copper-doped beryllium capsule with a smooth solid layer of DT on its inner surface. The radially tailored fusion capsule will be mounted at the centre of a 9 mm high by 5 mm diameter cylindrical hohlraum made of a material with high atomic number, such as gold.

For NIF to achieve ignition, the beryllium capsule must have a precise spherical shape. The capsule's surfaces must be smooth to within 1 nm—an unprecedented requirement

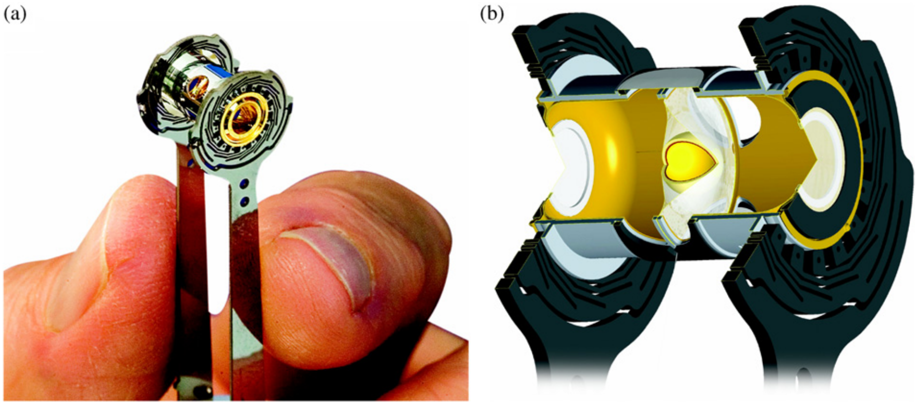

Figure 7. (*a*) NIF fusion target thermo-mechanical package, (*b*) cut-away drawing shows 2 mm fuel capsule supported at the hohlraum centre.

for surface roughness—and the thickness and opacity of the copper-doped layers must be carefully controlled. Each capsule is made by depositing beryllium on a smooth, perfectly spherical plastic mandrel. As the mandrel is rotated, a 150 μm thick layer of beryllium slowly builds up on its surface. After a capsule is polished, a laser is used to drill a 5 μm fill hole. An oxidation technique removes the mandrel through the drilled hole, and a 10 μm tube is attached to the capsule so it can be filled with DT gas.

Researchers at LLNL, LANL and LLE have pioneered procedures [12] to form the frozen layer of DT fuel inside the fuel capsule at 1.5° below the triple point of the DT mixture. Temperature can fluctuate no more than 1 mK—a demanding requirement for accuracy. Beta decay of the tritium helps smooth the layer by selectively heating thicker regions and evaporating hydrogen from them. The NIF researchers found that the DT ice can be shaped by precisely controlling heat transfer within the hohlraum, including contributions from thermal convection of helium. Auxiliary heaters located on the hohlraum shape the temperature field within the target to produce a nearly spherical isotherm. To control the ice layer's surface roughness, the NIF team developed a seeding and cooling procedure that achieves a surface roughness of about 0.5 μm (rms) at the solid–gas interface. A thermo-mechanical assembly encasing the target (figure 7) is able to maintain its position to within 2 μm, while holding it at 18 to 20 K with fluctuations limited to only 1 mK. This system integrates the ICF target with a cryogenic layering and characterization station and a target positioner attached to the NIF's target chamber. The system includes a positioning boom to centre the target in the chamber. An ignition-target inserter cryostat attached to the positioner cools the target and the DT fuel to meet temperature and uniformity requirements. The layering and characterization station can image the DT fuel layer along three axes within a few minutes.

To measure the performance of the lasers, hohlraum and target capsule and to record the results of NIF experiments, the target chamber is surrounded by dozens of detectors, oscilloscopes, interferometers, streak cameras and other instruments designed to capture reaction history, dynamic temperature and opacity of the target over dynamic ranges far greater than the capabilities of previous systems. The diagnostic instruments must be precisely positioned and aligned to capture data from the millimetre-size fusion target, operated remotely, and be able to quickly transmit vast amounts of data to instruments kept at a safe distance from the target chamber's harsh radiation environment, which will include neutrons, x-rays, gamma rays and electromagnetic pulses.

In NIF, about 35 different diagnostics will be used to study target behaviour with high accuracy and precision. Advanced ignition diagnostics planned for the NIC include:

- The Velocity Interferometer (VISAR) diagnostic for shock timing. The intense x-rays produced by the laser beams rapidly heat the outer surface of the spherical target, driving shock waves towards the target centre. VISAR uses sophisticated interferometric techniques to accurately measure the speed of these shock waves, with the information used to optimize design of the target.
- The Dante soft x-ray power diagnostic to characterize the x-rays generated by the experiments.
- A Cherenkov gamma-ray detector to measure the history of the hydrogen fuel's ignition and burn with 50 ps resolution.
- A magnetic recoil spectrometer for neutron spectroscopy.
- X-ray emission and backlit imaging system to image the target core as it ignites.

4. Exploring frontier science

NIF will also provide national and international researchers unparalleled opportunities to explore 'frontier' basic science in astrophysics, planetary physics, hydrodynamics, nonlinear optical physics and materials science. Up to 15% of NIF's time and resources will be devoted to science experiments in these fields. With its 192 beams together generating up to 1.8 MJ of energy, NIF will provide the highest temperatures and densities that have ever been created in a laboratory, enabling scientists to study some of the most extreme conditions in the universe, as the following examples illustrate.

The coupling of high-intensity laser light to plasmas has been the subject of experimental investigations for many years. Past experiments have focused on measuring a broad range of phenomena [13], such as resonance and collisional absorption, filamentation, density profile and particle distribution modification, and the growth and saturation of various parametric instabilities. These phenomena depend on the properties of the laser and the composition of the plasma. NIF's large, uniform plasmas and laser-pulse shaping, coupled with diagnostics that will measure the plasma's electron and ion temperature, charge state, electron density and flow velocity, make it an ideal site for studying these processes with new precision. Planned experiments include the evolution of plasma perturbations at the interface of two materials, stable and unstable high-Mach-number plasma flow, the transition to turbulence under extreme conditions, and multi-beam nonlinear optical processes in plasmas that can result in radiation fields propagating at new frequencies or in new directions.

The conditions that are expected to be produced by the NIF when it achieves ignition are extraordinarily well matched to the conditions that exist in stars in different phases of their evolution. Temperatures up to 100 million K and densities of 1000 g cm^{-3} are clearly in the stellar range, and the neutron density at ignition, possibly as high as 10^{26} cm^{-3}, with fluxes up to 10^{33} neutrons cm^{-2} s^{-1}, exceeds that of stellar nucleosynthesis [14].

Supernovae mark the death of massive stars by mechanisms not fully understood. The explosions are characterized by strong shocks and turbulent hydrodynamics. The NIF will replicate shock-induced nonlinear hydrodynamic instabilities in scaled laboratory experiments, although with spatial and temporal scales 10–20 orders of magnitude smaller than those of their astrophysical counterparts. The NIF will allow researchers to conduct the first detailed three-dimensional experiments of strong-shock-induced Rayleigh–Taylor instability. The laboratory experiments will help researchers better understand the mechanisms occurring in remnants and to verify the accuracy of computational models developed to interpret supernovae behaviour.

The stellar nucleosynthesis that produces heavy elements has been studied for several decades. While its properties are well established by the nuclear physics of the nuclei synthesized in it, where it occurs in the universe is not yet known. Leading candidate sites are core-collapse supernovae and colliding neutron stars. The NIF will be able to shed light on this question by providing an environment in which some of the reactions that affect the process can be studied. In addition, the very high neutron flux generated by ignition may even be able to create some of the neutron-rich nuclides that will help scientists better understand the properties of those nuclei as they are synthesized.

Black holes are one of the most exotic objects in the universe. Understanding the dynamics of matter as it spirals inwards towards a black hole is an enormous scientific challenge. Much of our understanding of black holes arises from observations of x-rays emitted by matter that is pulled into the deep gravitational wells of black holes. The extreme temperatures of these plasmas produce nuclei in very highly ionized states, with spectra quite different from atoms or slightly ionized ions. The NIF will create photoionized plasmas to test models and improve interpretations of x-ray data recorded by space-based observatories of accreting black holes and neutron stars and will provide essential information about temperatures and densities in such extreme environments.

Many of the key questions in planetary physics are related to fundamental questions in extremely dense condensed matter physics. In just the last few years, astronomers have discovered more than 150 new planets outside our solar system, including gas giants more than 15 times the mass of Jupiter and possible Earth-like planets more than 150 times Earth's mass. All of the 'extra-solar' planets discovered to date are giant or super-giant planets with interior conditions reaching pressures and temperatures as high as a gigabar and 10 000 K. Materials are known to undergo fundamental changes in their physical and chemical bonding properties at a fraction of such pressures, so there is considerable interest among scientists in experimentally observing materials at deep-planet conditions to better understand the makeup and geophysical evolution of these astronomical objects. The experimental data on the equation of state and other properties of hydrogen and helium are needed to test models of the interiors of Jupiter and Saturn and to better understand interior structures of the giant ice planets Uranus and Neptune. By providing new experimental capabilities for studying high-pressure, moderate-temperature states of condensed matter, the NIF will enable scientists to access the deep core states of large planets and answer some of the most fundamental questions in condensed matter physics.

5. The path towards inertial fusion energy

The primary motivation for fusion energy research is the promise of an energy source with no greenhouse gas emissions and with a virtually inexhaustible, widely available fuel supply. While these and other features of fusion energy are attractive, significant scientific and technological challenges remain. Conceptually, the ICF can be harnessed to generate electricity and other useful products from a steady sequence of ICF events. Fusion-power system studies indicate that the energy released per event could range from hundreds of megajoules to possibly as much as several gigajoules, with corresponding repetition rates from several per second to about once every 10 s for a 1 GW(e) power plant.

In addition to pure-fusion concepts, LLNL is pursuing a new fusion–fission hybrid technology called Laser Inertial Confinement Fusion–Fission Energy (LIFE). The LIFE concept is a logical extension of the NIF laser and the NIC discussed above. LIFE offers the possibility of providing sustainable, carbon-free energy while disposing of as much as 99% of the planet's nuclear waste and other hazardous nuclear materials. The LIFE concept consists of a relatively modest ICF neutron source surrounded by a spherical subcritical fission fuel blanket. In a LIFE engine, the point source of fusion neutrons acts as a catalyst to drive the fission blanket, which obviates the need for a critical assembly to sustain the fission chain reaction.

The key feature distinguishing LIFE from pure fusion is that ICF-generated neutrons induce fission reactions in this fuel, extracting virtually all its energy content and leaving a small residue of long-lived actinide waste. LIFE would thus close the nuclear fuel cycle without the need for chemical separation and reprocessing, while generating thousands of megawatts of carbon-free electricity. The system would require about half the laser energy input of a pure-fusion

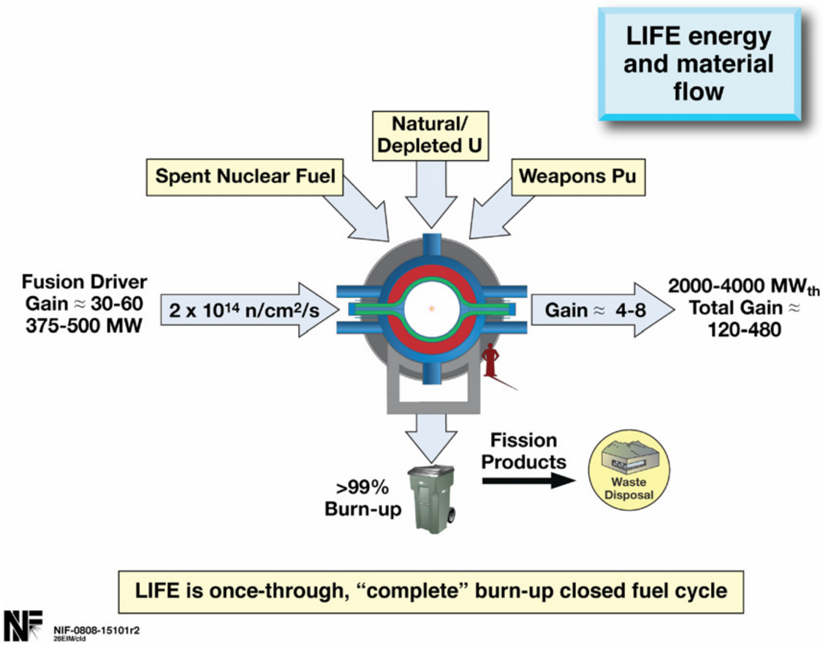

Figure 8. Schematic energy and material flow for the LIFE concept.

plant, produce about 200 times more energy than the input energy, be proliferation-resistant and passively safe, require no uranium isotope enrichment and minimize the need for long-term geologic storage of nuclear waste. LIFE would enable the worldwide expansion of nuclear power in a safe, secure and sustainable manner. Recent expert reviews of this concept have been positive, and LLNL researchers are on track to complete and review a point design and propose a specific development programme during the next year.

LIFE is a closed, self-contained system that breeds and burns its own fuel while generating gigawatts of electric power. The flow of material and energy in the LIFE concept is shown schematically in figure 8. LIFE would also be unattractive for nuclear proliferation, generating far less weapons-usable plutonium than a typical light-water reactor and incinerating more than 99% of the spent fuel and depleted uranium fuel. By generating minimal actinide high-level waste, LIFE would extend the useful service life of deep geologic repositories, such as the proposed repository at Yucca Mountain, Nevada, by a factor of 20. LIFE can burn a variety of fuels, including depleted or natural uranium, spent nuclear fuel, weapons-grade plutonium or highly enriched uranium, as shown in figure 8. A wide variety of alternative materials and fuel designs also are being evaluated and will be tested with a triple-beam accelerator.

The laser system needed for LIFE would deliver about 30 MW of average power in pulses at about 15 times per second and an electrical efficiency greater than 10%. A LIFE fusion driver based on NIF's multi-pass architecture would use high-power diode arrays and high-speed gas cooling technologies that have been developed and demonstrated as part of LLNL's mercury laser project [15]. LLNL has also developed large-scale, high-damage-threshold diffractive optics that would be used for the LIFE focusing optic and sophisticated targeting methods that would meet LIFE requirements. Emerging technologies, such as transparent ceramic laser materials, could further improve LIFE's performance and economics.

Challenges to the successful development of LIFE technology include achieving robust fusion ignition; the availability of low-cost, reliable diode-pumped solid-state lasers (DPSSLS) and low-cost, mass-produced fusion targets; completion of engineering and systems design and analysis; fabrication of a robust, long-lived inner wall, or 'first wall' for the reaction vessel; and development of fuel manufacturing methods for spent nuclear fuel and ultra deep-burn fuel.

The LIFE project complements and builds on the success of current and future nuclear energy technologies. A three-phase programme would lead to an operating demonstration plant by the mid-2020s: an R&D phase aimed at establishing the feasibility of the primary LIFE subsystems, construction of a pilot plant by 2020 capable of generating 3000 MW(e) and a commercial demonstration plant burning depleted uranium and spent nuclear fuel in 2024. The global introduction of LIFE power plants in the 2030s has the potential to reduce carbon dioxide emissions below today's levels. Among the potential spinoffs from the project are high-average-power lasers for manufacturing and materials processing; deep-burn fuels for nuclear energy applications, materials development and testing; and medical isotope production.

There are many technical challenges on the path to realizing commercial LIFE engines by the year 2030. The key technical challenges associated with the development of a LIFE fusion–fission engine include those related to achieving robust fusion ignition and burn on the NIF, the 10 Hz laser fusion driver, fusion targets, fission fuel and those associated with the operation of the fission engine.

- The NIF will execute one laser shot every few hours. A LIFE engine needs to execute on the order of 10 shots per second. This high repetition rate calls for diode-pumped solid-state lasers (DPSSLs) rather than flashlamp-driven lasers. Experts predict that diode costs used in

DPSSLs will continue to decrease significantly over the next several years, and many technologies required for DPSSLs have been demonstrated with the mercury laser system at LLNL.
- The LIFE engines will require several hundred million, low-cost targets per year that must be injected into the centre of the LIFE chamber at a rate of 10 to 20 s^{-1}.
- The first wall of the fission blanket will be exposed to large fluxes of fast neutrons and x-rays. Ongoing research in Japan, the EU and the United States is focused on developing new structural steels that are suitable for both fusion and fission reactors, and therefore also to the LIFE engine environment. Current and near-term oxide dispersion-strengthened (ODS) ferritic steels offer radiation limits of 150–300 dpa, which correspond to lifetimes of 4–8 y in a 2.5 m radius LIFE engine driven by a fusion power of 500 MW.
- Researchers are also investigating and producing new forms of fission fuel capable of withstanding extreme environments for increasingly longer periods. Completion of LIFE's energy mission will require high levels of burn-up in fertile fuels, and thus either development of advanced solid fuels or the adoption of a liquid fuel form.

Because of the 'separability' inherent in the LIFE concept, the science and technology for an integrated demonstration of the LIFE engine could be performed at the modular level in appropriately scaled facilities. For example, the demonstration of the required fusion gain could and would be done independently of the LIFE engine and the fission process. In fact, demonstration of mass production techniques for the fusion targets at required precision and cost scalability could be done 'off-line'. Similarly, target delivery, tracking and target engagement as well as chamber clearing could be demonstrated with surrogate targets and low-power lasers in separate facilities.

Although significant technical challenges must be met, LIFE is a promising approach to providing carbon-free, sustainable energy. Beginning in 2030, LIFE could be on a path to provide the majority of the US base load electricity demand into the existing grid. Spent nuclear fuel from light-water reactors could provide fuel for LIFE for the next 200 y, and depleted uranium from light-water-reactor fuel-enrichment could power LIFE engines for more than 1000 y. Another attractive feature of LIFE in contrast to traditional fission reactors is its subcriticality, which could ease regulatory requirements, reduce development and implementation costs and make the technology potentially more attractive to private industry. In sum, LIFE would enable the worldwide expansion of nuclear power in a safe, secure and sustainable manner, enhance US economic competitiveness and provide a path to sustainable energy security for the future.

6. Conclusion

After many years of R&D, all the pieces for ignition are in place: the NIF laser and the equipment needed for ignition, including high-quality targets and an ignition point design target. Initial ignition experiments will only scratch the surface of NIF's potential, including high yields with 2ω light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition using innovative fast ignition concepts.

All prior large laser facilities were designed and built with the latest technologies, and scientists then determined what research the facility could accomplish. In contrast, NIF was designed specifically to meet the needs of three missions: strengthen stockpile stewardship for a safe and reliable nuclear stockpile, advance ICF as a clean source of energy and to make significant strides in HED physics. These three missions share the need to expose materials to extraordinarily high pressures, temperatures and densities—as much as 100 billion atmospheres pressure, 100 million degrees Centigrade temperature and 1000 g cm^{-3} density. These conditions occur during thermonuclear burn, in supernovae, and in the fusion reactions that power our Sun and other stars and that may one day provide an inexhaustible power supply on earth. Because of the similarities of these phenomena, the results of some NIF experiments will be applicable to all three missions.

We cannot venture inside stars, planets or black holes, nor can we traverse billions of light years across the universe to examine a supernova explosion. However, with NIF, we can re-create in the laboratory the same physical processes that astronomers can only glimpse through a telescope. 2010 marks the golden anniversary of the demonstration of the first laser and the concept of ICF. Our goal with the NIC is to demonstrate ignition and burn and launch a new era of HED science and energy research.

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